

Using Paraffin PCM, Cryogel and TEC to Maintain Comet Surface Sample Cold from Earth Approach through Retrieval

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An innovative thermal design concept to maintain comet surface samples cold (for example, 263K, 243K or 223K) from Earth approach through retrieval is presented. It uses paraffin phase change material (PCM), Cryogel insulation and thermoelectric cooler (TEC), which are commercially available.

Nomenclature

<i>C</i>	=	carbon
<i>CSSS</i>	=	comet Sample Storage System
<i>EEV</i>	=	Earth Entry Vehicle
<i>H</i>	=	hydrogen
<i>N</i>	=	carbon number
<i>PCM</i>	=	phase change material
<i>TEC</i>	=	thermoelectric cooler

I. Introduction

COMETS are frozen chunks of ice and dust left over from our solar system's formation. Scientists want a closer look at them for clues to the origin of planets. A Comet Surface Sample Return mission is to obtain a sample from the surface of the nucleus of a comet, hermetically seal the sample within a capsule, return the sealed sample to an orbiting spacecraft, and return the sample to Earth for analysis in the laboratory. A rotating comet travels through the inner solar system at up to 241,000 km per hour and spews chunks of ice, rock and dust. NASA has been developing a comet harpoon for sample return. The concept is to avoid the risk of landing on the comet, but to grab a sample. Researchers want to send a spacecraft to rendezvous with a comet, then fire a harpoon to obtain samples rapidly from specific locations while hovering above the target. This technique allows sample collection even from surfaces that are too rugged or risky to allow landing and safe operation of a spacecraft. Fig. 1 shows an artist's concept of a comet harpoon embedded in a comet.

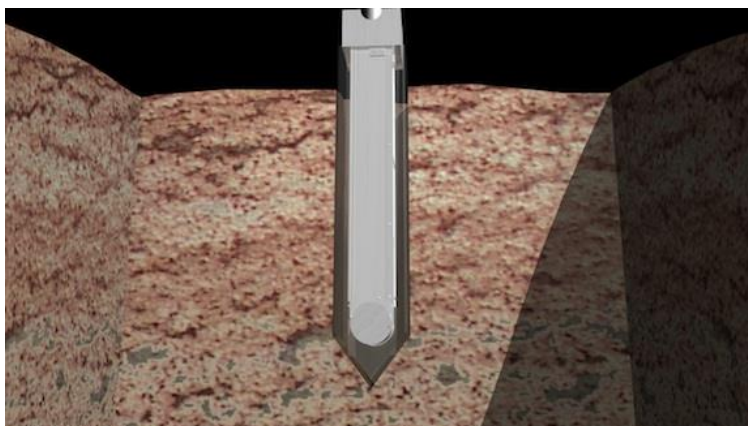


Figure 1. Artist's Concept of a Comet Harpoon Embedded in a Comet. (Source: NASA).

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The comet Sample Storage System (CSSS) is attached to an Earth Entry Vehicle (EEV). Fig. 2 shows the CSSS on the orbiter spacecraft after the comet ascent vehicle has been removed by a robotic arm. During the Earth Approach of the Return Cruise to Earth, the spacecraft may not maintain a thermally favorable attitude for CSSS passive cooling. Twelve hours after the EEV separates from the spacecraft, the CSSS will have been extracted from the EEV and deposited in a freezer. If the comet sample temperature needs to be in the 223K to 263K range during the Earth Approach through retrieval, and the thermal environment is significantly warmer than the requirement, heat transfer from the environment to the sample is significant. It is a challenge to maintain the sample temperature at or below the requirement before it is deposited in a freezer.

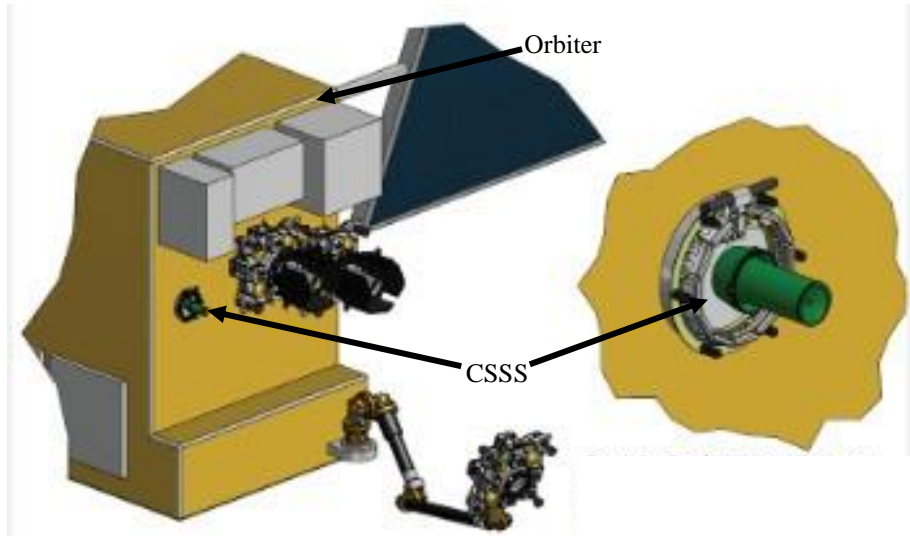


Figure 2. CSSS Remains on Orbiter Spacecraft. (Source: NASA).

II. Paraffin PCM, Cryogel and TEC to Maintain Comet Surface Sample Cold

The thermal design concept in this paper uses paraffin phase change material (PCM)¹⁻¹³, Cryogel thermal insulation¹⁴, and thermoelectric cooler (TEC) for a CSSS concept. Fig. 3 illustrates the concept. In this example, the CSSS canister contains four cartridges with comet return samples. Active cooling by TEC is needed only if the spacecraft cannot maintain a favorable attitude for passive cooling of the CSSS during the Return Cruise, including the Earth approach.

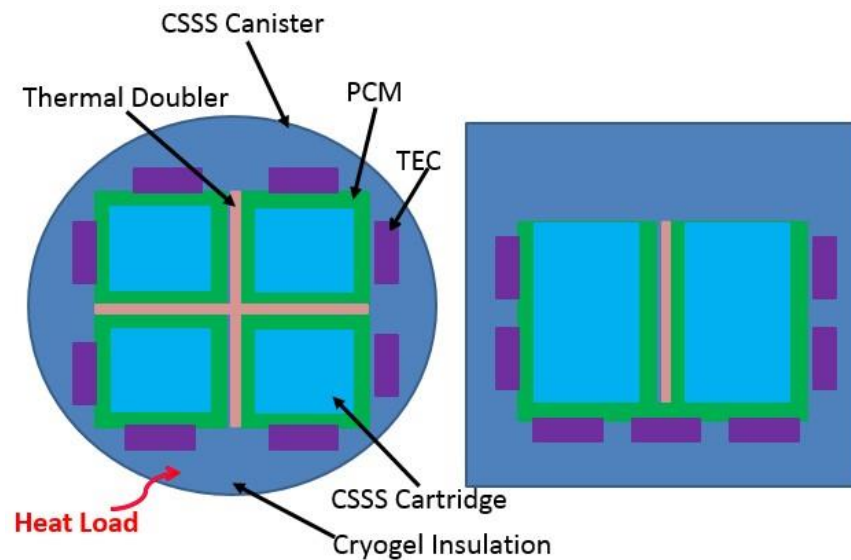


Figure 3. Paraffin PCM, Cryogel and TEC Thermal Design Concept.

Paraffin PCM is used to store thermal energy at a constant temperature. Fig. 4 shows the melting point of paraffin PCMs, that is in the 263K (-10°C) to 173K (-100°C) range, versus the carbon number (N). Fig. 5 shows the enthalpy of fusion versus the carbon number.

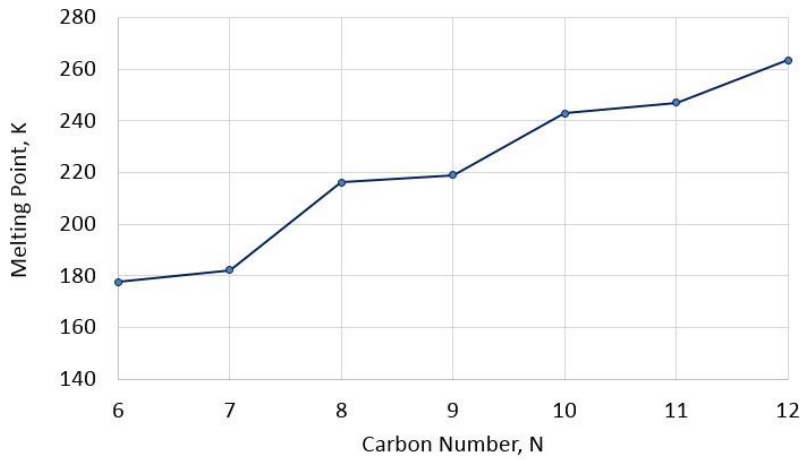


Figure 4. Melting Point of n-Alkanes (C_NH_{2N+2}).

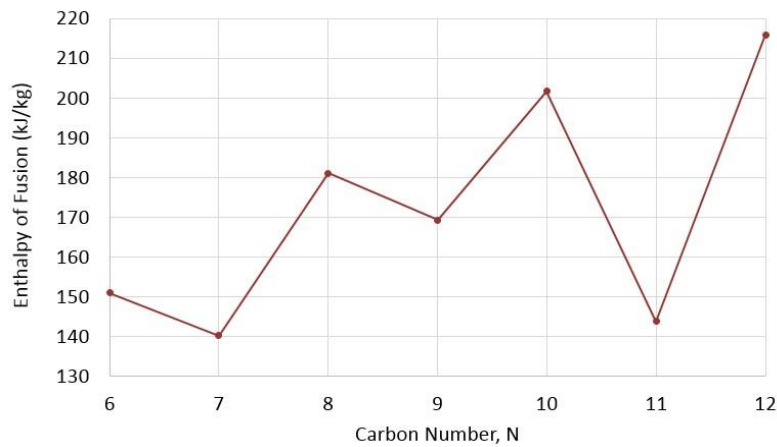


Figure 5. Enthalpy of Fusion of n-Alkanes (C_NH_{2N+2}).

Fig. 6 illustrates the solid-liquid phase front in a paraffin pack. It propagates as the PCM absorbs heat and melts. Fig. 7 shows the paraffin PCM melt and freeze cycle.

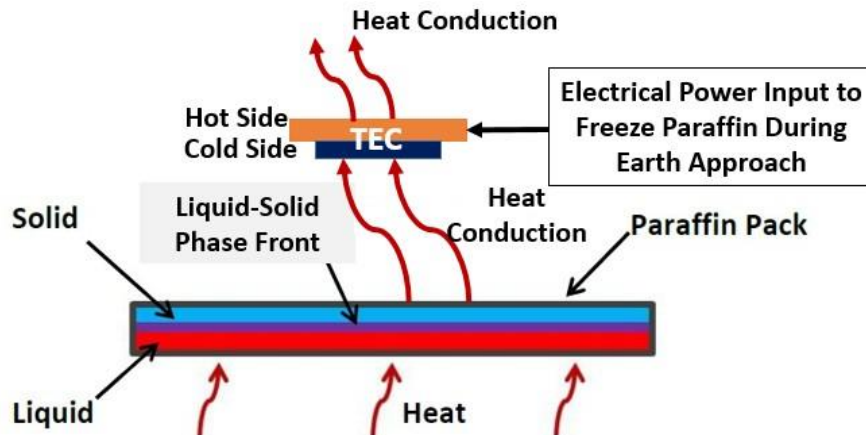
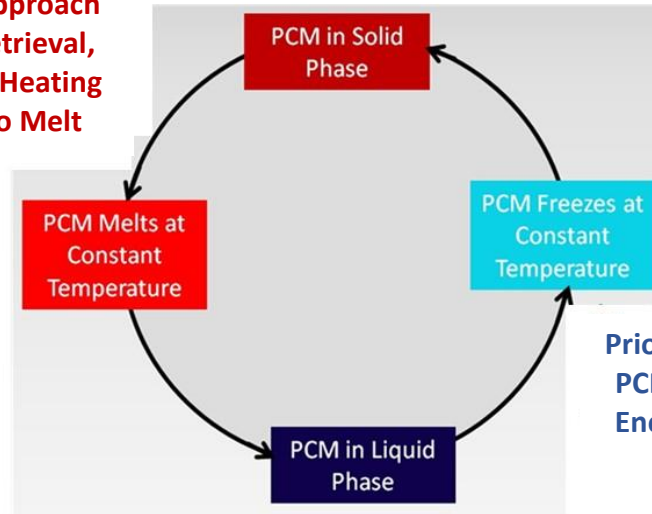


Figure 6. Solid-Liquid Phase Front in Paraffin Pack.

**During Earth Approach
and Prior to Retrieval,
Environmental Heating
Causes PCM to Melt**



**Prior to Earth Approach,
PCM Releases Thermal
Energy to Space or TEC
Cold Side**

Figure 7. Paraffin PCM Melt and Freeze.

Cryogel insulation, which is derived from aerogel, is used to minimize the heat load from the external environment or ambient to the comet samples. Fig. 8 presents the thermal conductivity of Cryogel measured by NASA Kennedy Space Center for cold and hot boundary temperatures of 78K and 293K, respectively.¹⁴

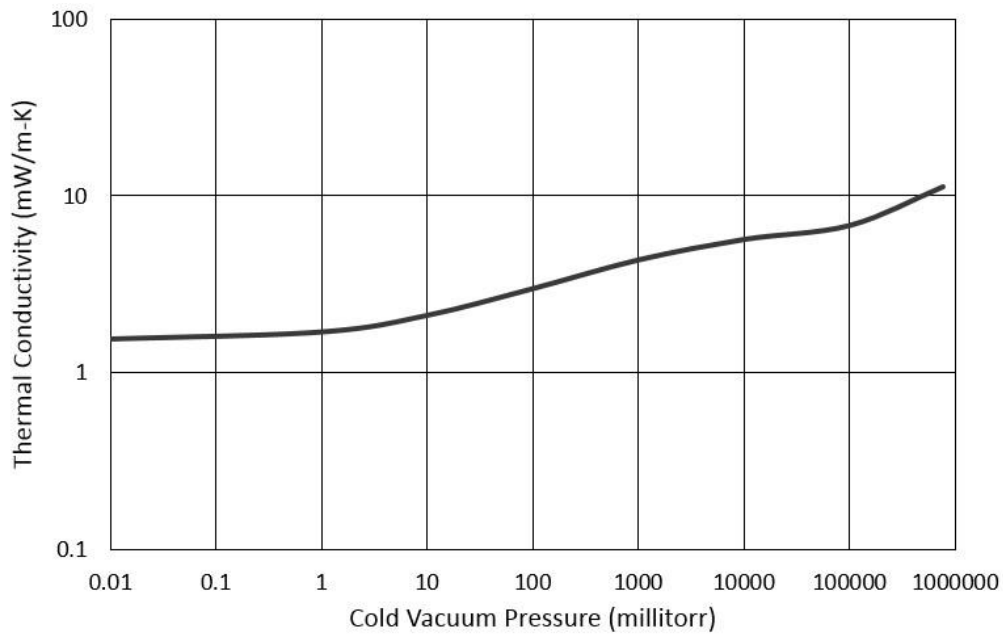


Figure 8. Thermal Conductivity of Cryogel.

As a case study, the comet sample temperature requirement is assumed to be 243K (-30°C). Prior to the CSSS separation, if the spacecraft thermal environment is warmer than 243K, TEC is used to cool the sample temperature to meet the 243K requirement. An umbilical harness between the EEV and spacecraft is required to supply electrical power to the TEC. A high thermal conductivity heat strap is used to transfer heat from the TEC hot side to the EEV.

The following assumptions are made to meet a 243K comet sample temperature requirement during the Earth Approach through retrieval. During the Return Cruise to Earth, with the EEV located on the anti-sun side of the spacecraft, the spacecraft is assumed to maintain a favorable attitude for passive cooling of the CSSS. However, as

the spacecraft approaches the Earth in preparation for EEV separation and re-entry, such a thermally favorable attitude is by no means guaranteed. Active cooling by TECs is used to assure the comet sample temperature to be maintained at 243K. Assuming the CSSS surface area to be 0.39 m², by using a 2.54 cm thick Cryogel insulation, which has a thermal conductivity of 1.5 mW/m-K in high vacuum,¹⁴ the thermal conductance is 0.023 W/K. Assuming the worst hot case temperature difference between the ambient and comet sample for the last 24 hours of Earth approach to be 50K, the heat load estimate is 1.15 W. Assuming a 60K temperature difference between the TEC hot side and cold side, the coefficient of performance (COP) is 0.1. To remove 1.15 W from the comet samples and PCM, 11.5 W of electrical power is required from the spacecraft during Earth Approach. The waste heat to be removed from the hot side of the TECs is 12.65 W. It is transferred by conduction to a radiator on the EEV. Multiple TECs are used to increase the thermal contact area for heat conduction.

During the 12 hours from separation through retrieval, assuming the worst hot case temperature difference between the ambient and comet samples is 80K. The thermal conductivity of Cryogel is 11.3 mW/m-K in ambient pressure. The heat load estimate is 13.9 W. The thermal energy absorbed by the PCM during these 12 hours is 600 kJ. Assuming n-Decane (C₁₀H₂₂) PCM, which has a 243K melting point and a 201.7 kJ/kg enthalpy of fusion, is used, the mass of PCM required is 2.975 kg. The volume of PCM (liquid at 50°C filled temperature) required is 4,391 cm³. Assuming the thickness of PCM is 2 cm, the area of PCM required is 2,196 cm². Approximately 1 kg of material is also required for encapsulation of the PCM.

If the comet sample temperature requirement is 263K (-10°C), the worst hot case temperature difference between the ambient and comet samples is 60K. The heat load estimate is 10.4 W. The thermal energy absorbed by the PCM during these 12 hours from separation through retrieval is 450 kJ. Then n-Dodecane (C₁₂H₂₆) PCM, which has a melting point of 263.3K (-9.7°C) and a 216 kJ/kg enthalpy of fusion, is used. The mass of the PCM required is reduced to 2.083 kg. The volume (liquid at 50°C filled temperature) required is reduced to 3,075 cm³. Assuming the worst hot case temperature difference between the ambient and comet sample for the last 24 hours of Earth approach to be 30K, the heat load estimate is 0.691 W. Assuming a 40K temperature difference between the TEC hot side and cold side, the COP is 0.4. To remove 0.691 W from the comet samples and PCM, 1.728 W of electrical power is required from the spacecraft during Earth Approach. The waste heat to be removed from the hot side of the TECs is 2.42 W.

If the comet sample temperature requirement is 223K (-50°C), the worst hot case temperature difference between the ambient and comet samples is 100K. The heat load estimate is 17.35 W. The thermal energy absorbed by the PCM during these 12 hours from separation through retrieval is 750 kJ. Then n-Octane (C₈H₁₈) PCM, which have a melting point of 216.3K (-56.7°C) and a 181.3 kJ/kg enthalpy of fusion, is used. The mass of the PCM required increases to 4.137 kg. The volume (liquid at 50°C filled temperature) required increases to 6,107 cm³. Assuming the worst hot case temperature difference between the ambient and comet sample for the last 24 hours of Earth approach to be 70K, the heat load estimate is 1.612 W. Assuming a 60K temperature difference between the TEC hot side and cold side, the COP is 0.1. To remove 1.612 W from the comet samples and PCM, 16.12 W of electrical power is required from the spacecraft during Earth Approach. The waste heat to be removed from the hot side of the TECs is 17.732 W.

Table 1 is a summary of the above thermal analysis for the Earth Approach. Table 2 is a summary of the above thermal analysis for the Earth Re-entry and Landing.

Table 1. Summary of Parameters for Earth Approach.

Comet Sample Temperature (K)	T _{ambient} - T _{sample} (K)	TEC Heat Load (W)	TEC T _{hot} -T _{cold} (K)	COP of TEC	TEC Power Input (W)	TEC Heat Removal (W)
263	30	0.691	40	0.4	1.728	2.420
243	50	1.150	60	0.1	11.500	12.650
223	70	1.612	60	0.1	16.120	17.732

Table 2. Summary of Parameters for Earth Re-Entry and Landing.

Comet Sample Temperature (K)	T _{ambient} -T _{sample} (K)	Heat Load (W)	Paraffin PCM	Enthalpy of Fusion (kJ/kg)	PCM Mass (kg)	PCM Volume (cm ³)
263	60	10.40	C ₁₂ H ₂₆	216.0	2.083	3075
243	80	13.90	C ₁₀ H ₂₂	201.7	2.975	4391
223	100	17.35	C ₈ H ₁₈	181.3	4.137	6107

If the spacecraft can maintain a favorable attitude for passive cooling of the CSSS during the Return Cruise, including the Earth approach, such that the comet sample temperature is colder than the requirement, active cooling by TECs is not required. In this case, only Cryogel insulation and paraffin PCM are needed.

III. Flight Heritage of Paraffin PCM, Cryogel and TEC

Two small paraffin packs (Fig. 9) are flown on the NASA MESSENGER Mercury Dual Imaging System (MDIS) instrument.² The paraffin is dodecane (C₁₂H₂₆). Paraffin panels (Fig. 10) were built for the GSFC Vegetation Canopy Lidar project.² There was no degradation after 5,000 thermal vacuum cycles. Three mini paraffin packs (Fig. 11) have been installed to the instrument on the IceCube CubeSat which will be launched from a nano-rack on the International Space Station (ISS). The paraffin is n-hexadecane (C₁₆H₃₄). The technology readiness level (TRL) of paraffin phase change material is at least 7.

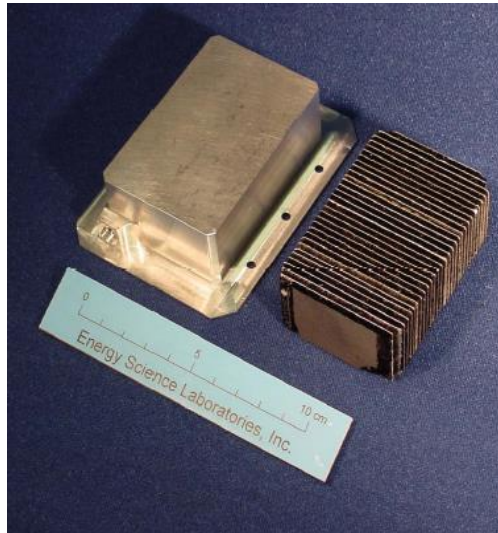


Figure 9. Paraffin Pack Flown on MESSENGER MDIS (~ 7 cm x ~5 cm Footprint).²



Figure 10. Paraffin Panel (25.4 cm x 25.4 cm x 1 cm) for NASA VCL Project.²

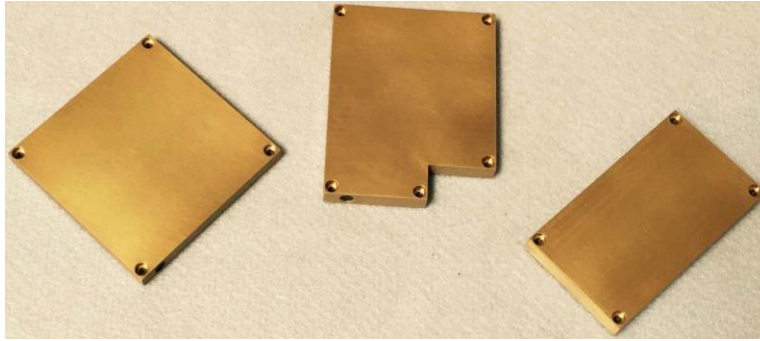


Figure 11. Flight Mini Paraffin Packs for IceCube CubeSat.

Silica aerogel thermal insulation, which Cryogel is derived from, was flown on Mars rovers, including Pathfinder, Spirit and Opportunity. Cryogel thermal insulation (Fig. 12), which is available from Aspen Aerogels, has been used by NASA for cryogenic insulation. It is flown on the General Laboratory Active Cryogenic International Space Station Experiment Refrigerator (GLACIER) (Fig. 13). It has been used on launch vehicles, including space shuttle external fuel tank's hydrogen vent umbilical system interface connection (Fig. 14). Additionally, it has been used on ground support systems, including launch tower and vehicle umbilical, space shuttle launch pad's fuel cell systems, and liquid oxygen lines of E-3 engine test stand at Stennis Space Center.¹⁵ The TRL of Cryogel thermal insulation is at least 7.

Cryogel thermal insulation is physically robust. It is durable, resilient flexible even at low temperatures, and resistant to mechanical abuse. It has excellent bounce-back properties, even when exposed to compression forces of hundreds of pound per square inch. It is capable to recover from high impact load compression events and maintain performance. Mechanical impact of sample return capsule landing is not expected to be an issue for Cryogel.

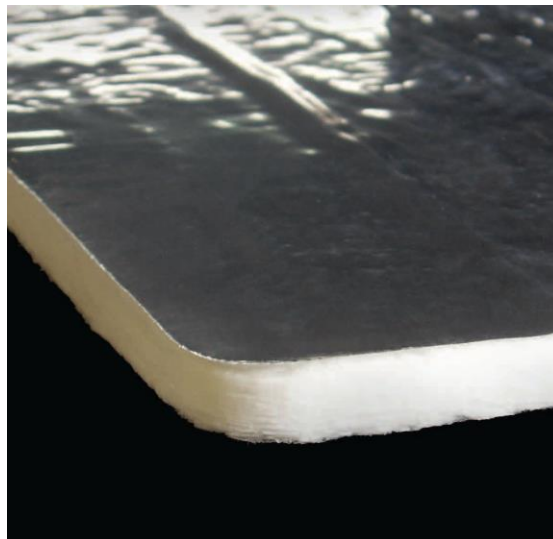


Figure 12. Cryogel Z. (Source: Aspen Aerogels).



Figure 13. GLACIER with Cryogel on ISS. (Source: NASA).



Figure 14. Cryogel for Protecting Critical Systems from Extremely Cold Hydrogen Used to Launch Space Shuttles. (Source: NASA).

TEC has high flight heritage. Examples are Solid-state Imaging Spectrometers (SIS) on the Advanced Satellite for Cosmology and Astrophysics (ASCA, originally Astro-D), X-Ray/Gamma-Ray Spectrometer (XGRS) instrument on the Near Earth Asteroid Rendezvous (NEAR) spacecraft, Wide Field Camera 3 (WFC3) on the Hubble Space Telescope, Multi-angle Imaging SpectroRadiometer (MISR) on the Earth Observing System (EOS) TERRA spacecraft, X-Ray Spectrometer (XRS) on the MERCURY Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER).

IV. Conclusion

This paper presents an innovative thermal design concept to maintain comet surface samples cold (for example, 263K, 243K or 223K) from Earth Approach through retrieval. It uses paraffin PCM, Cryogel thermal insulation and TEC, which are commercially available and have flight heritage. It prevents the comet surface sample temperature from exceeding the maximum limit at retrieval.

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